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Leader Bagging Improves Lateral Branching and Cropping Potential of 'Gala' and 'WA 38' Apple during Orchard Establishment

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Abstract. **Inadequate lateral branch development can lead to decreased apple (*Malus ×domestica* Borkh.) orchard productivity and profitability in modern high-density orchard systems. Although plant growth regulator applications are used to increase lateral branching on leaders of young apple trees, inconsistent responses have been observed in the southeastern United States. In North Carolina and Washington, three experiments were conducted to identify effective leader management strategies to increase lateral branching. Effects and interactions of leader bagging, 6-benzyladenine (6-BA), and 6-BA + gibberellic acid (GA_{4+7}) on lateral branch development of 1-year-old leaders were evaluated. Across all experiments, leader bagging was an influential factor. When compared with unbagged trees, leader bagging increased lateral branch number (20% to 48%), number of feathers (74% to 125%), average branch length (28% to 34%), and total linear bearing surface (428%) of the treated section of the leader. Blossom cluster density and final fruit set were increased in bagged trees, 65% and 36%, respectively. At the rates and timings tested, 6-BA and 6-BA + GA_{4+7} were generally ineffective in stimulating lateral branching and interactions among the factors evaluated were not influential. Leader bagging was an effective lateral branch induction strategy, although the mechanism of action is poorly understood. Future research to characterize the bagged environment and/or physiological responses to bagging may aid in the development of future environmentally sustainable technologies to stimulate lateral branching of apple trees.**

Inadequate lateral branching of young apple (*Malus ×domestica* Borkh.) trees is a yield limitation that can reduce orchard profitability (van Oosten 1978; Wertheim 1978). Incomplete canopy development ("blind wood") can result in reduced fruiting sites, canopy light interception, and subsequent yield potential. Apple yield and total dry matter production are positively associated with total light interception (Palmer et al. 2002). Sufficient lateral branching in young trees results in early, high yields (Ferree and Rhodus 1987; Jacyna 1996; Robinson and Stiles 1995) compared with leaders with blind wood. Blind wood occurs when lateral buds on 1-year-old wood do not break and produce shoots. As the tree ages, older buds are less likely to break, leaving a semipermanent, unproductive section of tree. Although blind wood is problematic in all orchard systems, modern high-density orchard systems are reliant on early production to offset the high cost of orchard establishment (Nieto et al. 2023; Robinson et al. 2007a). As a result, blind wood development during orchard establishment can result in significant financial losses.

Blind wood is more prevalent in some cultivars such as Fuji, Granny Smith, Honeycrisp, and WA 38, all of which demonstrate strong apical dominance. Trees with a type IV growing habit (Lauri 2007) are particularly prone to blind wood development. Polar auxin transport from the apical meristem and auxin:cytokinin levels in lateral buds are the main drivers in maintaining paradormancy, which leads to blind wood (Cline and Deppong 1999; Wang et al. 1994). When auxin:cytokinin levels are lowered, apical dominance is decreased and lateral buds break. Gibberellin can then induce shoot growth. Rootstock, cultivar, and environmental factors influence proclivity to lateral branching and success of plant growth regulator (PGR) treatments (Gąstoł et al. 2012; Saracoglu and Cebe 2018).

Strategies to induce lateral branching have been researched for more than 60 years, with many early efforts focused on canopy manipulation rather than chemical intervention. Methods such as heading (Ouellette et al. 1996), notching (Greene and Autio 1994), scoring/girdling (Musacchi and Greene 2017), leaf removal (Barlow and Hancock 1960), and bending (Mullins 1965; Myers and Ferree 1983) have been variably effective at inducing lateral branch growth. Although not completely understood and characterized, it is thought that canopy manipulation strategies rely on physical disruption of the tree's hormone signaling pathways. Most of these canopy manipulation techniques (heading, notching, and scoring/girdling) interrupt apical dominance and the flow of auxin to lateral buds (Cline and Deppong 1999; Greene and Autio 1994; Rufato et al. 2020). Removal of undeveloped apical leaves is thought to reduce auxin sources (Theron et al. 1987). Bending results in redistribution of growth hormones, including increased ethylene evolution (Robitaille and Leopold 1974) and decreased polar auxin transport and cytokinin levels (Sanyal and Bangerth 1998).

In low- and moderate-density orchard systems, dormant-heading cuts have historically been used to induce lateral branching; however, they stimulate vigorous shoot growth and can reduce crop yield (Robinson et al. 2007b). Vigorous shoots that develop proximal to heading cuts can be detrimental in high-density orchard systems that aim for high light interception and canopy uniformity. Heading cuts on young trees can have long-lasting detrimental effects (5 years) on reproductive and vegetative growth (Elfving 1990) and are generally discouraged in modern apple orchard production systems.

Notching is an effective method in stimulating lateral branching of 1-year-old wood (Greene and Autio 1994) and when used in conjunction with 6-benzyladenine (6-BA) can stimulate lateral branching on >2-year-old wood (McArtney and Obermiller 2015). Because notching is a labor-intensive and time-sensitive activity, this approach to stimulate lateral branching is generally reserved as a remedial treatment.

Leaf removal at the shoot apex is an effective lateral branch induction strategy and improved the efficacy of 6-BA + gibberellic acid [GA_{4+7} (Theron et al. 1987)]. Snaking/bending of the leader had mixed responses on lateral branching. Although leader snaking increased the number of lateral branches (Parker and Young 1995), an uneven distribution of lateral branches and labor costs are disincentives for adoption (Ouellette et al. 1996).

Central leader bagging is an uncommon orchard management practice and research is limited. Strydom (1993) was the first to report the practice of leader bagging as a lateral branching strategy. Bagging is done by affixing a polyethylene sleeve over the previous year's unbranched growth immediately after

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planting (Fig. 1). Alternatively, in second- or third-leaf orchards, bags are deployed ~4 to 6 weeks before anticipated budbreak. Once shoots extend to 2.5 to 5.0 cm, bags are opened or cut to allow tissues to acclimate to open air. After 4 to 6 d, polyethylene sleeves are removed (Becker 2020; Parker et al. 1998). In general, a subsequent application of 6-BA + GA_{4+7} is recommended to promote further extension of laterals (Becker 2020; Parker et al. 1998). Central leaders that were bagged on the 1-year-old wood portion of the tree produced 3.7 more shoots with a length >5 cm when compared with untreated wood and increased total lateral growth by 149 cm per tree (Stasiak and Roper 1994).

The mechanisms of action of bagging are poorly understood. It is assumed that bagging modifies the microclimate of the unbranched leader, creating a "greenhouse effect" on a small section of the canopy (Becker 2020). This localized microclimate modification may provide a competitive advantage to vegetative meristems in the bagged environment. Although bagging appeared to be an efficient means to induce lateral branch production, this practice is not widely used commercially and limited research has been published in this area. Relative to PGR applications, this practice is expensive, as significant labor inputs are required to deploy and remove polyethylene sleeves.

Apples grown in high-density training systems on dwarfing rootstocks experience variable lateral branching in response to PGRs. Previous studies have shown that synthetic cytokinins, such as 6-BA, can induce lateral branching. When applied early season, 6-BA and GA_{4+7} alone and in combination increase shoot growth in current-season shoots (Elfving and Visser 2005, 2006; Hrotkó et al. 1999; Jacyna 2002). In apple, 6-BA and GA_{4+7} increased branching on 1-year-old wood in orchards (Elfving 1984; Ouellette et al. 1996; Unrath and Shaltout 1985) and in nursery production (Lordan et al. 2017; Robinson and Sazo 2014; Rufato et al. 2020; Saracoglu and Cebe 2018). Gąstoł et al. (2012) found that regardless of formulation, 6-BA and GA_{4+7} were able to promote lateral shoot growth, increasing the percentage of feathers, lateral number, and total lateral length in cultivars with low lateral development.

Notably, environmental conditions (temperature and irradiance) influence PGR uptake and efficacy, and multiple applications of 6-BA and GA_{4+7} are desirable for maximum lateral number and extension (Robinson and Sazo 2014; Rufato et al. 2020). In some climates, spring temperatures may be too low for optimal product performance, although it is notable that optimal temperatures for chemical branching agents have not been identified. Parker and Young (1995) suggested that the extended growing season in the southeastern United States results in increased annual leader growth, relative to northern climates. This can result in an excess of 1.5 m of unbranched leader growth on trees during orchard establishment (Parker and Young 1995). Excessive vigor in this environment has been suggested as a potential reason for inconsistent responses with chemical branching strategies, although this relationship has not been formally evaluated.

In high-density orchards, treatments of 6-BA and GA_{4+7} have been generally effective at lateral branch induction in young trees (first and second leaf). However, inconsistent responses were reported on older trees in the southeastern United States by members of the southeastern apple industry (Kon, personal communication). Because 6-BA and GA_{4+7} are widely adopted, other cultural management strategies to induce lateral branching have been underresearched. In addition, development of effective practices to minimize blind wood development on new, commercially important cultivars is critical to optimize production (Anthony et al. 2020). In this study, we investigated the effects and interactions of leader bagging, 6-BA, and 6-BA + GA_{4+7} on lateral branch development and productivity. We expected that the combination of the aforementioned cultural and chemical management practices would have a synergistic interaction and enhance lateral branching of apple.

Fig. 1. Leader bagging is conducted by affixing a polyethylene sleeve over the previous year's unbranched growth immediately after planting (**A**). Alternatively, in second- or third-leaf orchards, bags are deployed ~4 to 6 weeks before anticipated budbreak. This localized microclimate modification may provide a competitive advantage to vegetative meristems in the bagged environment and stimulate lateral branch development (**B**). Once shoots extend to 2.5 to 5.0 cm, bags are opened or cut to allow tissues to acclimate to open air (**C**). After 4 to 6 d, polyethylene sleeves are removed.

Materials and Methods

Expt. 1

In 2017, a 2-year experiment was initiated to identify effective leader management strategies on third-leaf 'Gala'/'M.9-RN 29' trees at a commercial orchard in Edneyville, NC (lat. 35.408539°N, long. 82.358154°W). Trees were planted in a northeast-southwest orientation at 0.9 × 4-m spacing and were trained to tall spindle. Commercial management practices for fertility, pesticide, and herbicide applications adhered to local recommendations in both years of the study. The planting was unirrigated. A total of 96 uniform trees were selected and flagged. Treatments were assigned in a completely randomized design with a 2 × 3 × 2 factorial treatment structure. The experimental unit (treated section) was the current season's growth of the central axis (leader) on a single tree. Three factors were evaluated in a factorial treatment structure: leader bagging (bagged or unbagged), 6-BA (500 $mg \cdot L^{-1}$ 6-BA; applied at green tip, silver tip, or untreated), and 6-BA + GA_{4+7} at ~3-cm branch extension (250 $mg \cdot L^{-1}$; treated or untreated).

Leader bagging occurred at the silver tip stage of bud development on 5 Mar 2017. Bagged leaders were enclosed in a 96.5 × 10.2-cm section of 4-mil polyethylene tubing (S-1143; Uline, Pleasant Prairie, WI, USA) and secured using clothespins. Silver tip (ST) and green tip (GT) applications of 6-BA (500 $mg \cdot L^{-1}$; Maxcel®, Valent Biosciences, Libertyville, IL, USA), occurred on 5 Mar 2017 and 29 Mar 2017, respectively. 6-BA was applied in an aqueous solution with a 5-cm paint roller. In situations in which treatment combinations required both leader bagging and 6-BA at GT, bags were removed briefly to facilitate application and were immediately redeployed.

On 18 Apr 2017, all bags were cut longitudinally to allow tissues to acclimate to open air once lateral branches were ~3 cm long. Bags were completely removed on 25 Apr 2017. On 29 Apr 2017, 6-BA + GA_{4+7} [250 mg·L^{-1} + 0.2% (v:v) nonionic surfactant (Regulaid®; KALO, Inc., Overland Park, KS, USA)] was applied using a backpack sprayer. Lateral branches were ~3 to 5 cm in length at this time.

Lateral branch measurements. During dormancy in Jan 2018, the basal circumference and length of the treated section was measured. Basal circumference was used to calculate leader cross-sectional area (LCSA). The number and length of all lateral branches of the treated section of the leader were recorded. In addition, terminal shoot extension of the leader was measured. Branches were counted and categorized by length as spurs (<1 cm), shoot (1.0 to 9.9 cm), or feather (≥10 cm). Average lateral branch length, terminal growth, and total linear bearing surface (the total length of all lateral branches) of the treated area were calculated.

Fruit set, blossom cluster density, and yield responses. Fruit set on the treated section was determined in 2017. After June drop, the number of fruit on the treated section was determined and used to calculate crop density (fruit no./LCSA). In Spring 2018, the number of blossom clusters of the treated section was counted. Blossom cluster density was calculated as the number of blossom clusters per unit LCSA. As part of the commercial grower's management program, all trees were chemically thinned. After June drop, the number of fruit on the treated section was determined and used to calculate crop density (fruit no./LCSA). Because chemical thinning was insufficient, all trees were also hand-thinned to a commercial standard. Fruit originating from the treated section was harvested at commercial maturity and was transported to NC State University's Mountain Horticultural Crop Research and Extension Center in Mills River, NC, USA. Fruit number, fruit weight, and yield were determined with an electronic fruit sorter (Durand-Wayland, Inc., LaGrange, GA, USA) outfitted with a load cell, color and infrared camera system, and full transmittance spectrometer (TrueSort Electronics; Ellips, Eindhoven, the Netherlands).

Statistical analysis. Effects and interactions of bagging (two levels), 6-BA (three levels), and 6-BA+GA_{4+7} (two levels) were evaluated using a completely randomized design with a factorial treatment structure. The experiment was replicated eight times. Main effects and interactions were determined using a three-way analysis of variance (ANOVA) using PROC GLM. The personal computer version of SAS (SAS 9.4, Cary, NC, USA) was used for all statistical analysis.

Expt. 2

An experiment was initiated in a newly planted commercial orchard near Quincy, WA, USA (lat. 47.259236°N, long. 119.857897°W). 'WA 38'/'M.9-RN 29' trees were planted in 0.8 m × 3.4-m spacing of north-south facing rows on 6 Apr 2018. Trees were trained as tall spindle axe on a vertical trellis with under-tree drip irrigation. Tree height was uniform (~2 m) and remained unheaded at planting. Experimental design was randomized complete block design with a factorial treatment structure and eight replicates. Experimental units were whole trees. Three factors were evaluated: leader bagging (bagged or unbagged), 6-BA (500 ppm or untreated), and 6-BA + GA_{4+7} (500 ppm or untreated).

Central leaders were bagged on 9 Apr 2018 in a similar fashion as described in Expt. 1. Instead of securing bags with clothespins, nylon cable ties were used. Approximately 8 cm of the polymer sleeve extended past each cable tie creating a treated length of 76 cm. On 9 Apr, all 6-BA treatments were applied. The 6-BA treatments were applied with a stain applicator pad (Blue Hawk; Lowe's, Mooresville, NC, USA). On 3 May 2018, when shoot extension inside the bag averaged 2.5 cm, the bags were opened but not removed to allow for acclimation. On the same day, foliar applications of 500 ppm of each PGR were applied with a handheld atomizer trigger sprayer (Professional Spray Bottle; ZEP, Atlanta, GA, USA). Leader bags were removed completely on 7 May, and 6-BA + GA_{4+7} applications were applied 4 days later, where appropriate.

Lateral branch measurements. The treated section was evaluated by counting and categorizing new lateral branching as spurs (<3 cm length), shoots (3.0 to 9.9 cm length), or feathers (≥10.0 cm length).

Statistical analysis. Effects and interactions of bagging (two levels), 6-BA (two levels), and 6-BA + GA_{4+7} (two levels) were evaluated using a completely randomized design with a factorial treatment structure. The experiment was replicated eight times. Main effects and interactions were determined using

Table 1. Main effects of leader bagging, 6-BA, and 6-BA + GA_{4+7} on the number of lateral branches, break length, total linear bearing surface, and terminal shoot length of third-leaf 'Gala'/'M.9-RN 29' in Edneyville, NC, USA. Budbreak data were collected on 29 Jan 2018.

	No. of breaks				Avg break length (cm)	Total linear bearing surface[i] (cm)	Terminal length (cm)
Factor	Total no.	Spur (<1 cm)	Shoot (≥1–9.9 cm)	Feather (≥10 cm)			
Bag (BAG)[ii]							
Yes	25	1.9	8.6	14.3	16.5	401.4	44.5
No	20	1.8	11.4	6.7	12.0	229.5	53.3
6-BA (BA)[iii]							
GT	23	2.1	10.6	10.5	13.5	315.6	50.3
ST	22	1.7	10.3	10.1	12.8	291.0	47.7
No	21	1.6	8.9	10.9	16.4	342.2	48.6
6-BA + GA_{4+7} (BA+GA)[iv]							
Yes	22	1.2	9.3	11.2	15.3	337.6	47.6
No	23	2.4	10.5	9.8	13.3	296.4	50.0
Significance[v]							
BAG	<0.0002	0.7554	0.0055	<0.0001	0.0016	<0.0001	0.0789
BA	0.5258	0.5676	0.3248	0.7264	0.0872	0.2335	0.9443
BA+GA	0.4290	0.0025	0.2608	0.1197	0.1506	0.1165	0.6464
BAG × BA	0.8137	0.3285	0.9815	0.2031	0.4997	0.2913	0.6667
BAG × BA+GA	0.6279	0.2119	0.7611	0.8354	0.6227	0.7857	0.7124
BA × BA+GA	0.5210	0.7389	0.2405	0.5371	0.4949	0.4342	0.5739
BAG × BA × BA+GA	0.2039	0.6648	0.1562	0.7314	0.5851	0.8136	0.9503

[i] Total linear bearing surface is the summation of the length (cm) of all lateral breaks and the terminal shoot originating from the treated section of canopy.

[ii] Leader bagging treatment occurred at silver tip bud stage 5 Mar 2017. Bagged leaders were enclosed in a 96.5 × 15.2-cm section of 4-mil polyethylene tubing and secured using clothespins. Bags were opened on 18 Apr 2017 and removed on 25 Apr 2017.

[iii] 6-BA = 500 mg·L^{-1} 6-benzyladenine in an aqueous solution. Applications occurred at silver tip (ST) and green tip (GT) on 5 Mar 2017 and 29 Mar 2017, respectively.

[iv] BA + GA = 6-BA + gibberellic acid (GA_{4+7}) [250 mg·L^{-1} + 0.2% (v/v) nonionic surfactant] was applied on 29 Mar 2017.

[v] F test significance. Three-way analysis of variance was performed using PROC GLM (SAS 9.4, Cary, NC, USA). The experiment had a 2 × 3 × 2 factorial treatment structure with eight replications.

a three-way ANOVA. The personal computer version of SAS (SAS 9.4, Cary, NC, USA) was used for all statistical analysis.

Expt. 3

In 2018, an additional study was implemented in the same orchard as Expt. 2. The experimental design was randomized complete block design and was replicated eight times. Treatments were as follows: 1) untreated control, 2) bagging, 3) bagging + 500 ppm 6-BA, and 4) bagging + 500 ppm 6-BA + GA_{4+7}.

For this study, the 6-BA was applied, and leaders were bagged on 10 Apr 2018 (4 d after planting). Applications were made with a stain applicator pad as described in Expt. 2. In contrast to Expts. 1 and 2, the top 8 cm of the central leader was left exposed instead of enclosed in the plastic sleeve. As in Expt. 2, ~76 cm of blind wood was enclosed in the sleeves.

On 3 May, when shoot extension inside the bags averaged ~2.5 cm long, the cable ties were removed from top and bottom, but the open sleeves were left on the trees to allow the tender new growth time to acclimate before full environmental exposure. On May 7, sleeves were removed completely; and on May 11, the 500 ppm 6-BA + GA_{4+7} application was made with a handheld atomizer trigger sprayer. A nonionic surfactant was included at 0.2% (v/v).

Initial measurements. On 17 Oct 2018, new lateral branching in the ~76-cm section of initial blind wood was counted and categorized as spurs (<3.0 cm length), shoots (3.0–9.9 cm length), or feathers (≥10.0 cm length).

Statistical analysis. Data were analyzed using the personal computer version of SAS (SAS 9.4; SAS Institute, Cary, NC, USA). ANOVA was performed using PROC MIXED. Tukey's honestly significance test was used to compare treatment means at $P = 0.05$.

Results and Discussion

Expt. 1. Leader bagging (BAG) was the only factor that influenced total budbreak (Table 1). BAG increased total budbreak by 20% and break length by 28% when compared with unbagged leaders. Treatments including 6-BA + GA_{4+7} (BA+GA) had a 44% decrease in spur counts compared with those without; however, there was no effect on total breaks. The main effect of BAG decreased shoots (25%) and increased feathers (115%) relative to treatments void of leader bags. Average break length and total linear bearing surface were increased in bagged treatments by 34% and 42%, respectively. Terminal growth was not influenced by any factor. An increase in linear bearing surface provides more area for fruit production, especially in subsequent years as spurs and shoots form on feathers.

Fruit set in 2017 and blossom cluster and crop densities in 2018 were evaluated across treated sections of central leaders. Only BAG had a statistically significant effect on all metrics (Table 2). In 2017, the year of treatment implementation, no fruit were set within bagged treatments and unbagged treatments had an average of three fruit. Lack of fruit set is beneficial on 1-year-old wood of leaders, as this fruit is of poor size and quality, and can reduce vegetative growth of trees during orchard establishment. This fruit would ultimately be removed in commercial production. Abortion of blossom clusters at different phenological stages was observed (Fig. 2). Although BAG may have interfered with pollination, it is possible that elevated temperatures

Table 2. Main effects of leader bagging, 6-BA, and 6-BA + GA_{4+7} on fruit set of 'Gala'/ 'M.9-RN 29' in 2017 and blossom cluster density and crop density in 2018 in Edneyville, NC, USA.

	Fruit set 2017	Blossom cluster density	Crop density
Factor	Fruit no./LCSA[i]	no./LCSA	fruit no./LCSA
Bag (BAG)[ii]			
Yes	0	25.8	12.5
No	3	15.6	9.2
6-BA (BA)[iii]			
GT	2	18.4	10.3
ST	2	20.8	11.1
No	1	21.8	10.9
6-BA + GA_{4+7} (BA+GA)[iv]			
Yes	2	19.2	10.9
No	1	21.4	10.7
Significance[v]			
BAG	<0.0001	<0.0001	0.0003
BA	0.569	0.3088	0.7116
BA+GA	0.2785	0.2812	0.6599
BAG × BA	0.569	0.3270	0.1138
BAG × BA+GA	0.2785	0.7299	0.8192
BA × BA+GA	0.0826	0.2489	0.4856
BAG × BA × BA+GA	0.0826	0.3365	0.5015

[i] LCSA = leader cross-sectional area (cm^2).
[ii] Leader bagging treatment occurred at silver tip bud stage 05 Mar 2017. Bagged leaders were enclosed in a 96.5 × 15.2-cm section of 4-mil polyethylene tubing and secured using clothespins. Bags were opened on 18 Apr 2017 and removed on 25 Apr 2017.
[iii] 6-BA = 500 $mg \cdot L^{-1}$ 6-benzyladenine in an aqueous solution. Applications occurred at silver tip (ST) and green tip (GT) on 5 Mar 2017 and 29 Mar 2017, respectively.
[iv] BA+GA = 6-BA + gibberellic acid (GA_{4+7}) [250 $mg \cdot L^{-1}$ + 0.2% (v/v) nonionic surfactant] was applied on 29 Mar 2017.
[v] P(F). Three-way analysis of variance was performed using PROC GLM (SAS 9.4, Cary, NC, USA). The experiment had a 2 × 3 × 2 factorial treatment structure with eight replications.

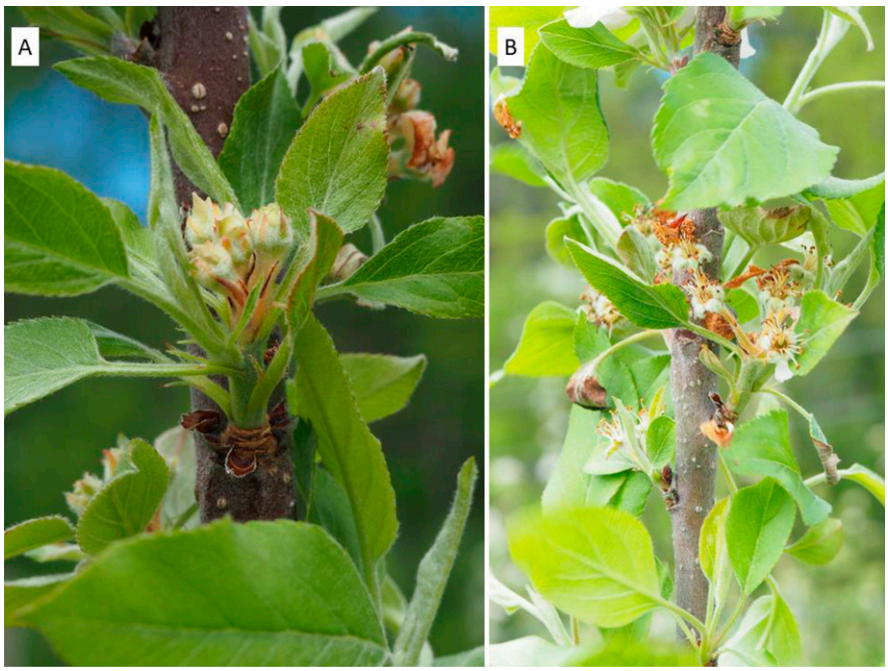

Fig. 2. Observed abortion of reproductive structures at pink bud stage (**A**) and post bloom (**B**). Leader bagging impaired fruit set in the year of treatment. This response may be due to elevated temperatures in the bagged environment and/or physical exclusion of pollinators.

in the bagged environment hastened the degradation and/or limited the receptivity of reproductive tissues. In the year after treatment (2018), BAG increased blossom cluster density of the treated section by 65% and crop density by 36% (Table 2). The observed increase in linear bearing surface (38%) and crop density (36%) was proportional. Increasing the productive bearing surface of trees during orchard establishment has long-term benefits related to orchard uniformity and yield.

In this study, neither PGR treatment nor timing improved lateral branching and downstream effects of higher blossom cluster density and fruit set. We acknowledge that ST applications of these PGRs was earlier than what is recommended. Our results are contrary to previous literature that found 6-BA and 6-BA + GA_{4+7} to be effective at increasing lateral branching (Elfving 1984; Ouellette et al. 1996; Unrath and Shaltout 1985). It is notable, however, when treatments were applied at 5 to 20 cm terminal shoot extension (Elfving 1984; Unrath and Shaltout 1985) that lateral branch induction was increased with PGRs. In addition, environmental conditions and number of applications have a significant effect on uptake and activity of PGRs used to induce lateral branching (Robinson and Sazo 2014; Rufato et al. 2020). In our research, it is likely that 6-BA was applied too early to be effective. However, BA+GA was applied when recommended (Becker 2020; Parker et al. 1998) and had limited benefit.

Expt. 2. Leader bagging was the only factor with a significant effect on total budbreak and shoot number (≥3–9.9 cm; Table 3). BAG increased budbreak by 38% and shoot number by 266.7%. Both BAG and BA+GA had significant main effects on spur number (<3 cm) and feather number (>10 cm). BAG and BA+GA both reduced spur number by 61% and 45%, respectively. Feather number was increased by BAG and BA+GA by 54% and 20%, respectively. There were no interactions between treatments, suggesting that bagging alone had the greatest impact on budbreak, and even types of breaks that eventually form. These results confirm those found in Expt. 1. Leader bagging increases budbreaks, leading to greater linear bearing surface in following years. The use of PGRs was variably effective, but not as impactful as bagging.

Expt. 3. All treatments, excepting the untreated control, in Expt. 3 included leader bagging, and all resulted in increased budbreaks and feathers and decreased spurs (Table 4). Leader bagging is the variable driving the increase in budbreaks, as BAG + 6-BA and BAG + 6-BA + GA_{4+7} were not significantly different from BAG alone. Leader bagging resulted in a 42.9% increase in total budbreak and a 125% increase in number of feathers on the treated section compared with the untreated. In Expts. 2 and 3, leader bagging of blind wood on first leaf 'WA 38' trees 3 or 4 d after planting significantly increased lateral branching by as much as 48%, and number of feathers by as much as 129%, over untreated trees.

Table 3. Main effects of leader bagging, 6-BA, and 6-BA + GA_{4+7} on lateral break number and break classification of first leaf 'WA 38'/ 'M.9-RN 29' in Quincy, WA, USA.

	No. of breaks			
Factor	Total	Spur (<3 cm)	Shoot (≥3−9.9 cm)	Feather (≥10 cm)
Bag (BAG)[i]				
Yes	22	1.3	1.1	20
No	16	3.3	0.3	13
6-BA (BA)[ii]				
GT	20	1.9	0.5	17
No	19	2.6	0.9	16
6-BA + GA_{4+7} (BA+GA)[iii]				
Yes	20	1.6	0.7	18
No	19	2.9	0.7	15
Significance[iv]				
BAG	<0.0001	<0.0001	0.0090	<0.0001
BA	0.8148	0.0759	0.1139	0.1507
BA+GA	0.4882	0.0020	0.9500	0.0404
BAG × BA	0.8212	0.9188	0.0599	0.3976
BAG × BA+GA	0.5628	0.1046	0.2130	0.3492
BA × BA+GA	0.9508	0.7945	0.1139	0.6683
BAG × BA × BA+GA	0.8597	0.1302	0.3031	0.4720

[i] Leader bagging treatment occurred 3 d after planting (9 Apr 2018). Bagged leaders were enclosed in a 76 cm × 10.2-cm section of 4-mil polyethylene tubing and secured using cable ties. Bags were opened on 3 May 2018 and removed on 7 May 2018.
[ii] 6-BA = 500 mg·L^{-1} 6-benzyladenine in an aqueous solution. Application occurred on 9 Apr 2018.
[iii] BA+GA = 6-BA + gibberellic acid (GA_{4+7}) [500 mg·L^{-1} + 0.2% (v/v) nonionic surfactant] was applied on 11 May 2018.
[iv] P(F). Three-way analysis of variance was performed using PROC GLM (SAS 9.4, Cary, NC, USA). The experiment had a 2 × 3 × 2 factorial treatment structure with eight replications.

The understanding of the mechanism of bagging central leaders to induce budbreak is still speculative. Theories related to a "greenhouse effect" when bags are applied may have some merit, as temperatures inside bags likely stay elevated, potentially hastening bud development (Becker 2020). The unanswered part of that theory relates to whether there is a disruption of apical dominance. It is not likely because the most apical meristem is contained in the bag, in the same environment as the underdeveloped buds, and therefore still has an advantage. Terminal buds were enclosed during BAG in Expt. 2, but were exposed in Expt. 3. BAG was effective in stimulating lateral branch development in both situations. Others have suggested an accumulation of ethylene and/or CO_2 within the bag, although this remains unproven and untested. Characterizing the BAG environment and physiological differences between bagged and unbagged leaders should be considered in future research. We acknowledge that increased use of non-recyclable plastics in agricultural systems is not an environmentally sustainable practice. However, based on this research, we suggest that future development of sustainable technologies to selectively modify canopy microclimate would be of great value and potentially provide an effective nonchemical approach to stimulate lateral branching in apple.

Leader bagging is an effective strategy to stimulate lateral branching; however, it is important to note the time and labor investment that must be made to implement this treatment. Timely deployment and removal of polyethylene sleeves is a requisite for success and delayed removal can result in injury of leaf tissue or mortality of lateral branches (Fig. 3). The authors estimated that each year that this treatment would be implemented on a leader would cost ∼$0.57 USD per leader. This assumes that labor costs for BAG were

Table 4. Comparison of three lateral branching treatments and an untreated control on lateral break number and break classification of first leaf 'WA 38'/'M.9-RN 29' in Quincy, WA, USA.

	Total breaks	Spur (<3.0 cm)	Shoot (≥3.0–9.9 cm)	Feather (≥10 cm)
Control	14 b[i,ii]	6 a	0 b	8 b
Bag[iii]	20 a	2 b	0 ab	18 a
Bag + 6-BA[iv]	20 a	1 b	2 a	16 a
Bag + 6-BA + GA_{4+7}[v]	20 a	1 b	1 ab	18 a

[i] Means of eight observations.
[ii] Mean separation within columns by Tukey's honestly significant difference test at $P = 0.05$.
[iii] Leader bagging treatment occurred 4 d after planting (10 Apr 2018). The top 8 cm of the central leader was left exposed and the subtending a 76-cm section was enclosed in 4-mil polyethylene tubing and secured using cable ties. Bags were opened on 3 May 2018 and removed on 7 May 2018.
[iv] 6-BA = 500 mg·L^{-1} 6-benzyladenine in an aqueous solution. Application occurred on 9 Apr 2018.
[v] 6-BA + gibberellic acid (GA_{4+7}) [500 mg·L^{-1} + 0.2% (v/v) nonionic surfactant] was applied on 11 May 2018.

Fig. 3. Observed foliar injury (**A**) and mortality of lateral branches (**B**) following removal of polyethylene sleeves used in leader bagging. This injury may be due to desiccation of succulent tissues during acclimation and/or high temperature injury.

$0.29 USD (assuming an hourly wage of $15 USD per hour and ∼1.18 min for installation) and materials were ∼$0.27 USD per leader.

Conclusion

Across three experiments and two locations, leader bagging was an effective method to stimulate lateral branching. In the subsequent year, increased bearing surface corresponded with increased reproductive potential and crop density. Additional research is required to better understand the mechanisms of lateral branching in the bagged environment. At the timings and concentrations evaluated, PGR treatments were relatively ineffective in inducing lateral branching. Limited responses of PGRs in this research may be related to the timing or concentrations used. Optimizing use patterns and identifying environmental conditions for PGRs used to stimulate lateral branching should be considered in future research.

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